International Conference on Thermoelectrics: Caen, France

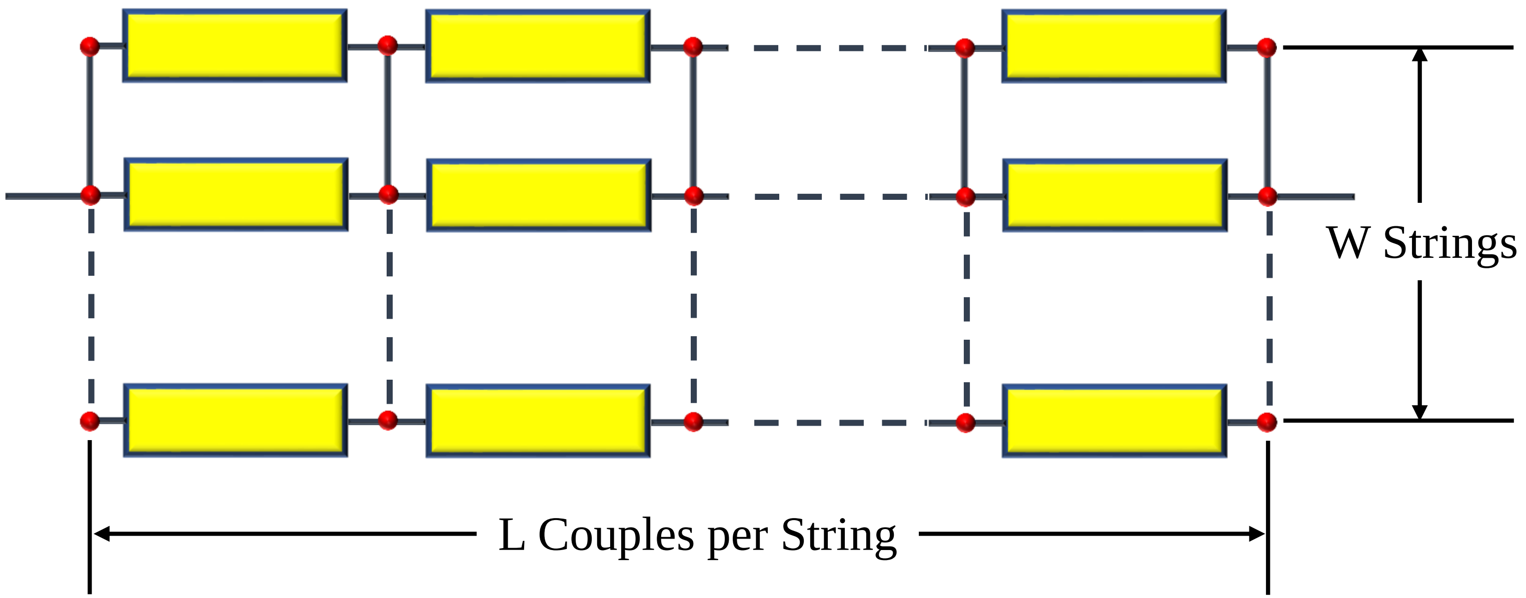
A Study on the Reliability of Thermoelectric Couple Networks

Christopher Matthes, Chester Everline, David Woerner, Terry Hendricks

Jet Propulsion Laboratory
California Institute of Technology

Network Architecture

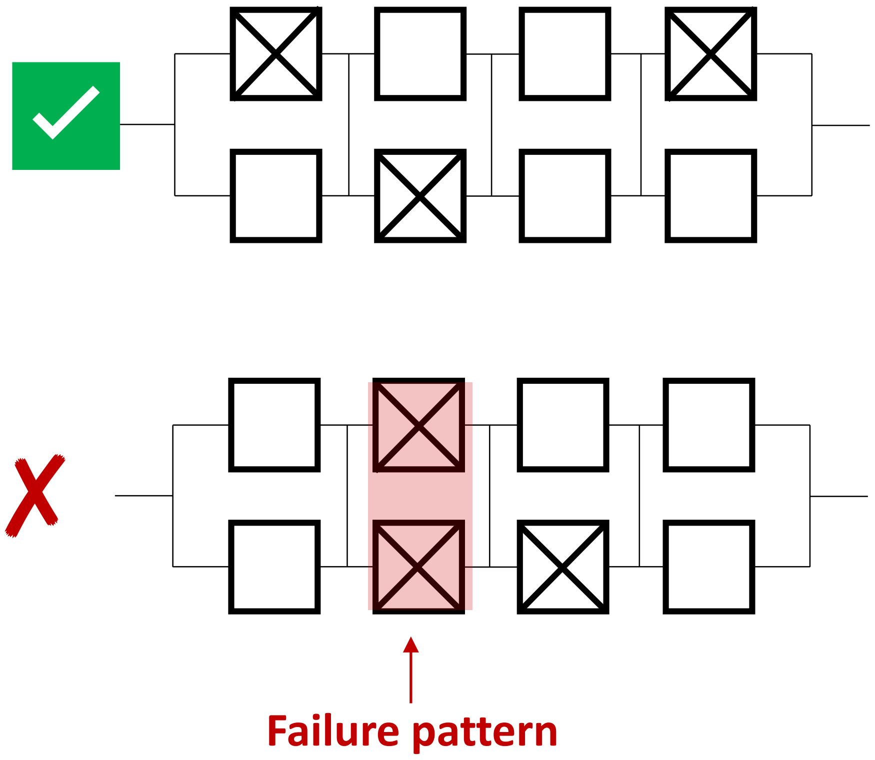
- The model is based on a thermoelectric couple (TC) network consisting of W redundant, fully cross-strapped strings (series-parallel circuit) with L couples per string, as depicted below.
- This model considers only catastrophic failure (due to loss of electrical continuity), and therefore is generally most valid for cantilevered TC designs.



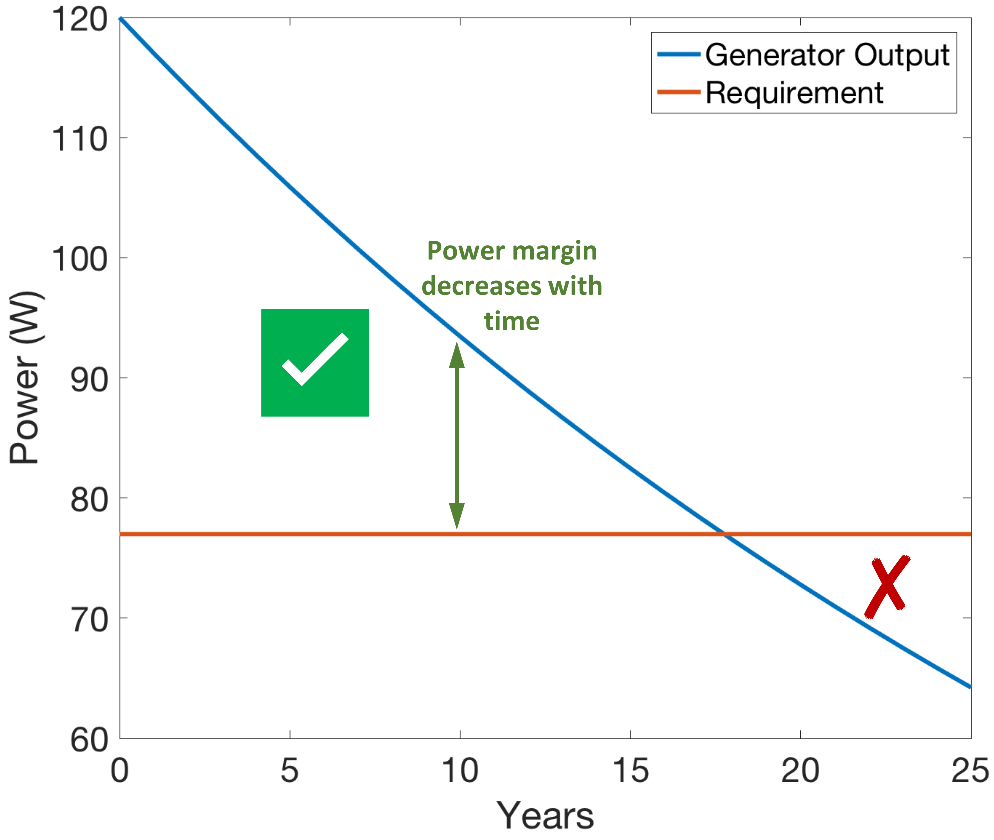
Total # of couples in the network: **m = W*L**

Requirements for success

1. Electrical continuity

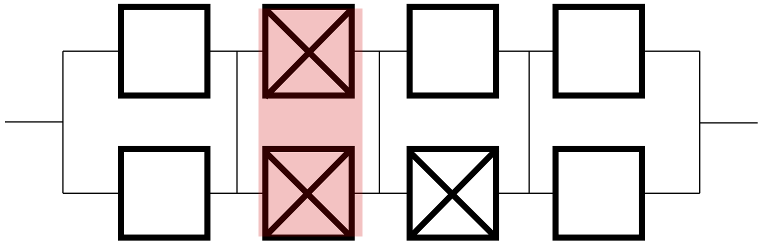


2. Sufficient power output



Generator Reliability Model[1]

Failure pattern



$$R_G = \sum_{i=0}^{j} \left[\binom{m}{i} - F_i \right] R_C^{m-i} [1 - R_C]^i$$

Number of possible **arrangements** of i failures in a network of m couples

Number of possible **failure patterns** for i failures

j = maximum number of allowable failures
= (Power output—Power requirement)/(Power per couple)

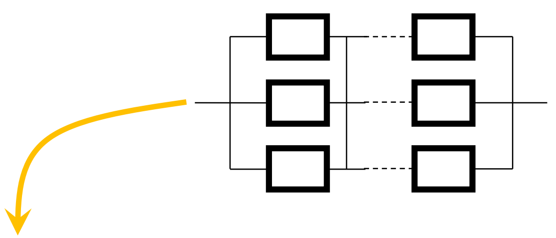
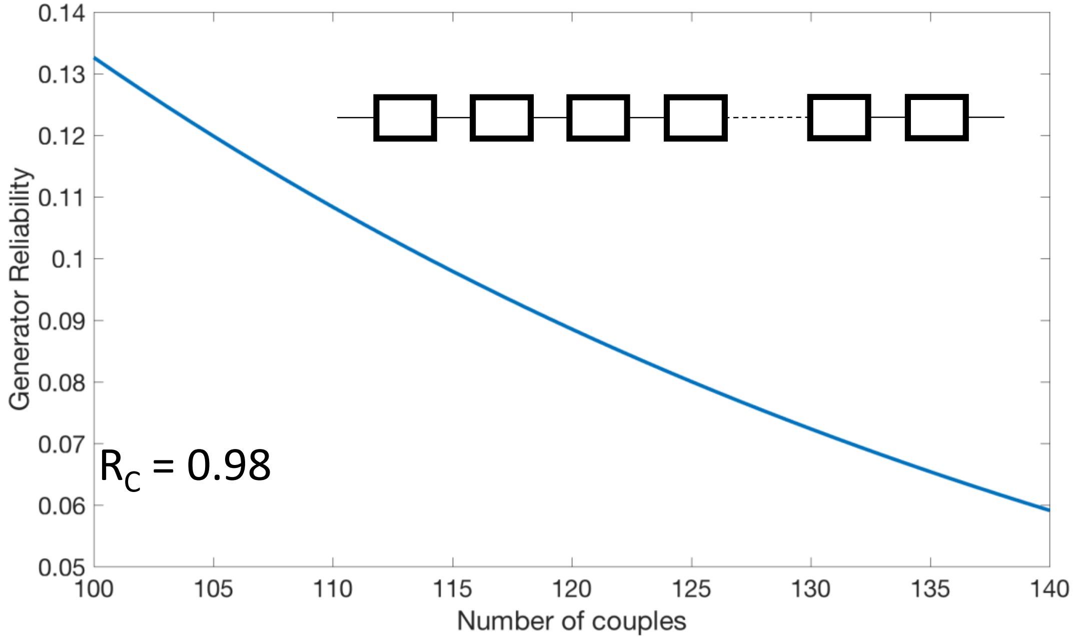
R_C = couple reliability $= e^{-\lambda t}$ $\lambda = {}^{1}/_{MTBF}$
m = total number of couples in network

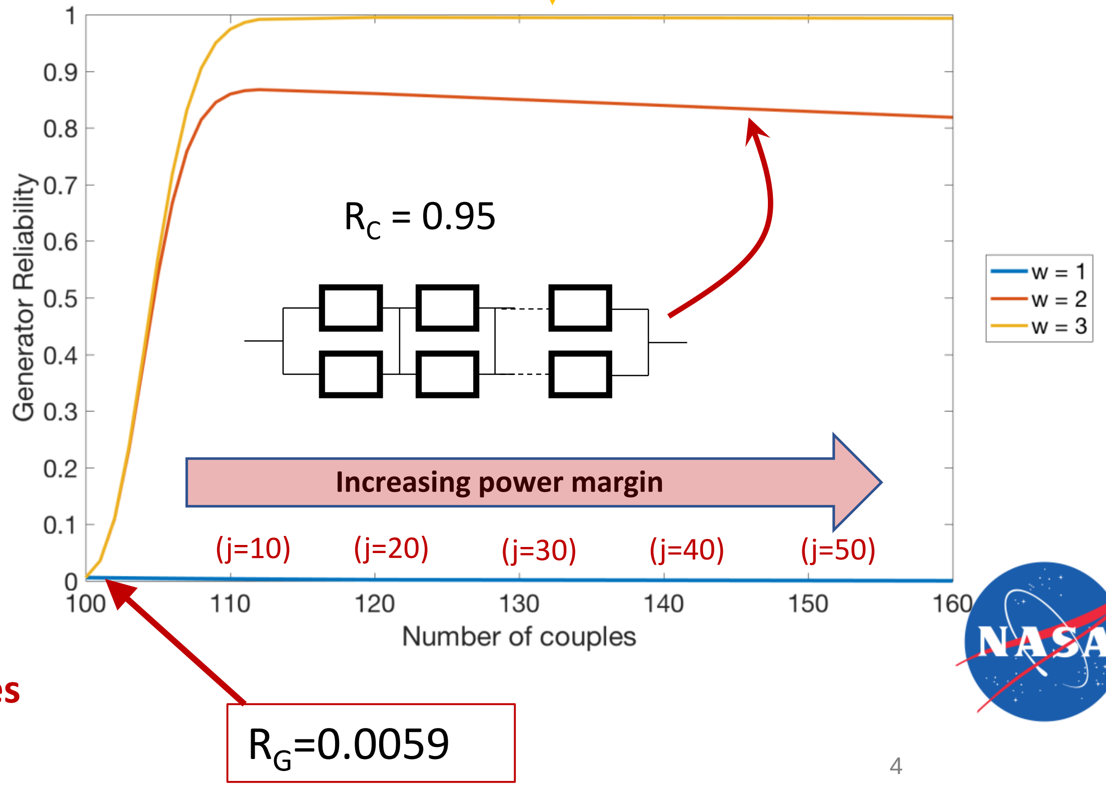
- This is a binomial distribution problem, where the reliability is described by the cumulative distribution function, minus the probability of encountering a failure pattern
- Goal is to assess **generator reliability** R_G using a defined **couple reliability** R_C by expressing the probability of having ***j* or fewer failures**, without encountering a **failure pattern**
- F can be determined using a Monte-Carlo analysis, but a closed-form solution of this model was developed and used for the following numerical results

[1] Karr, C. H., "Reliability of Thermoelectric Couple Networks Based Upon Couple Catastrophic Failure," *IEEE Transactions on Reliability*, Vol. R-19, No. 3, August 1970, pp. 116-119.

Sensitivity study: Network Architecture

- **Reconfiguring** a network containing a defined number of couples into single, two, and three-string cross-strapped architectures affects reliability
- **Voltage** requirement will define constraints on required length of strings
- As # of couples increases, there are more opportunities for **failure patterns** to occur, causing reliability to decrease after a maximum
- Lower couple reliability necessitates more strings to achieve acceptably high generator reliability

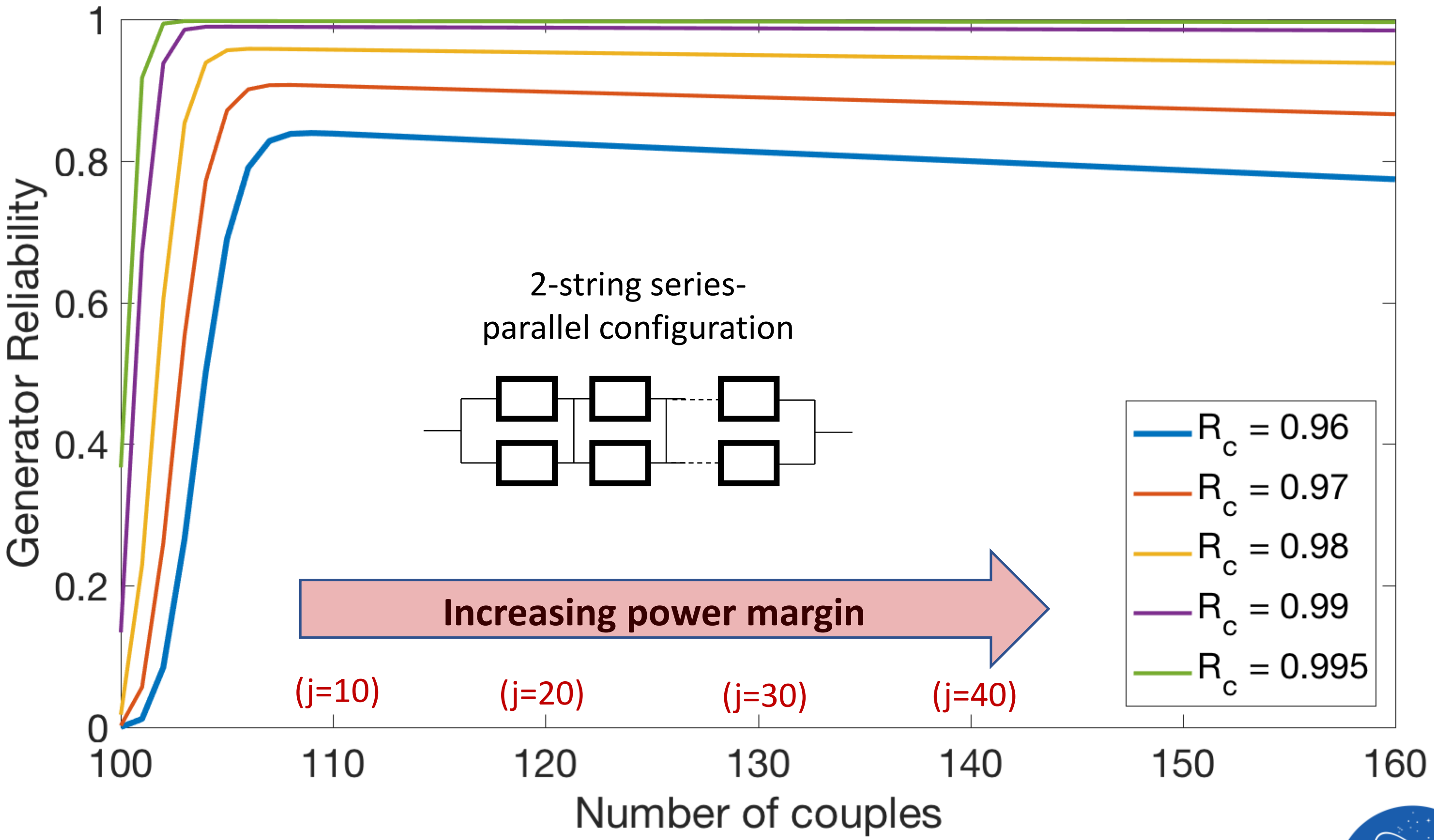





***Power requirement achieved here with at least 100 operable couples**

Sensitivity study: Couple Reliability

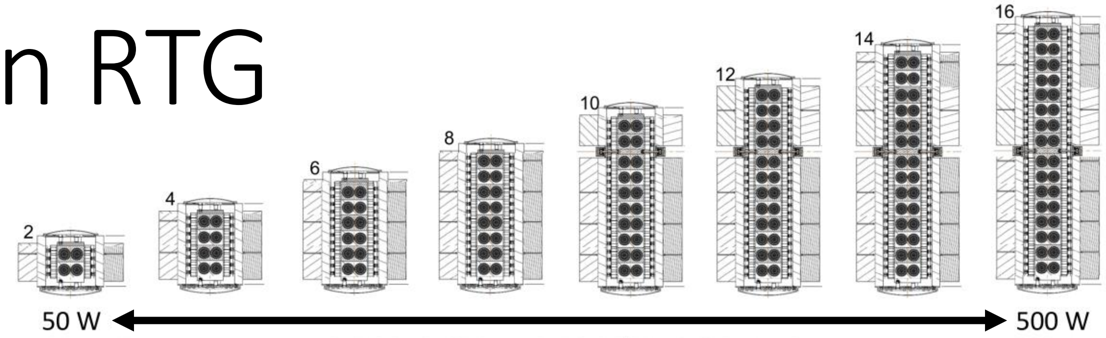
- Adding couples to the network **increases the margin** between the power output and the requirement, but does not always result in higher overall reliability
- R_G reaches a **peak** and then begins to decrease with additional couples to the network
- Higher R_C:
  - Results in a higher overall R_G
  - Reaches peak with lower power margin (needs less insurance)
  - R_G declines more slowly after reaching peak (harder to experience a failure pattern)



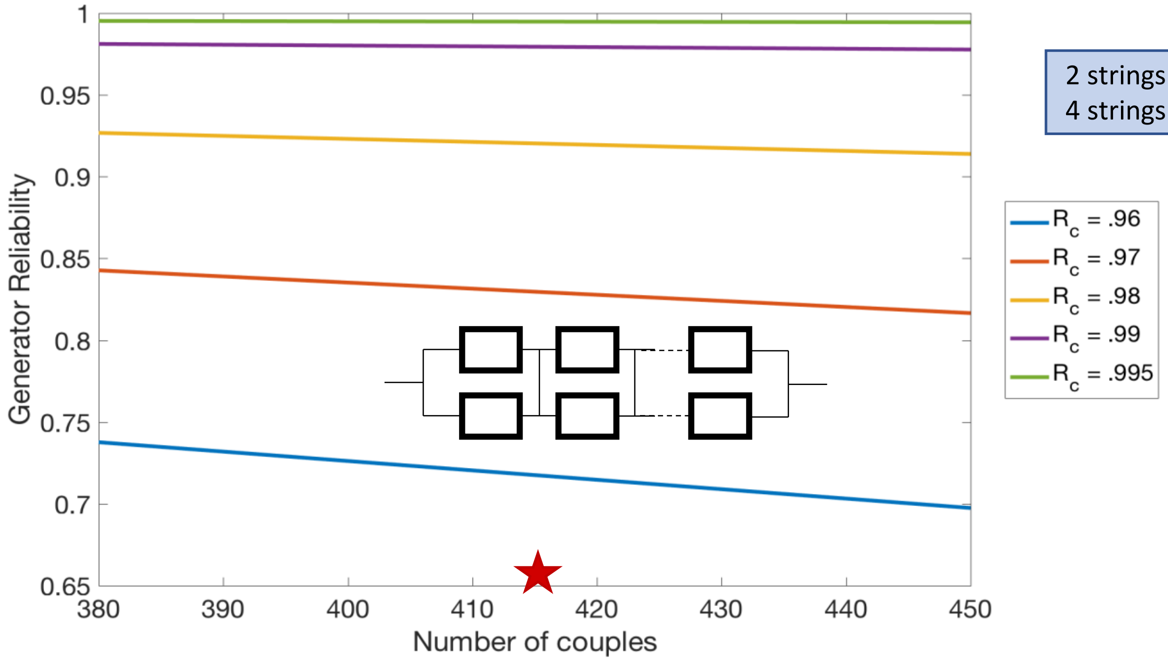
***Power requirement achieved here with at least 100 operable couples**

Example: Next-Generation RTG

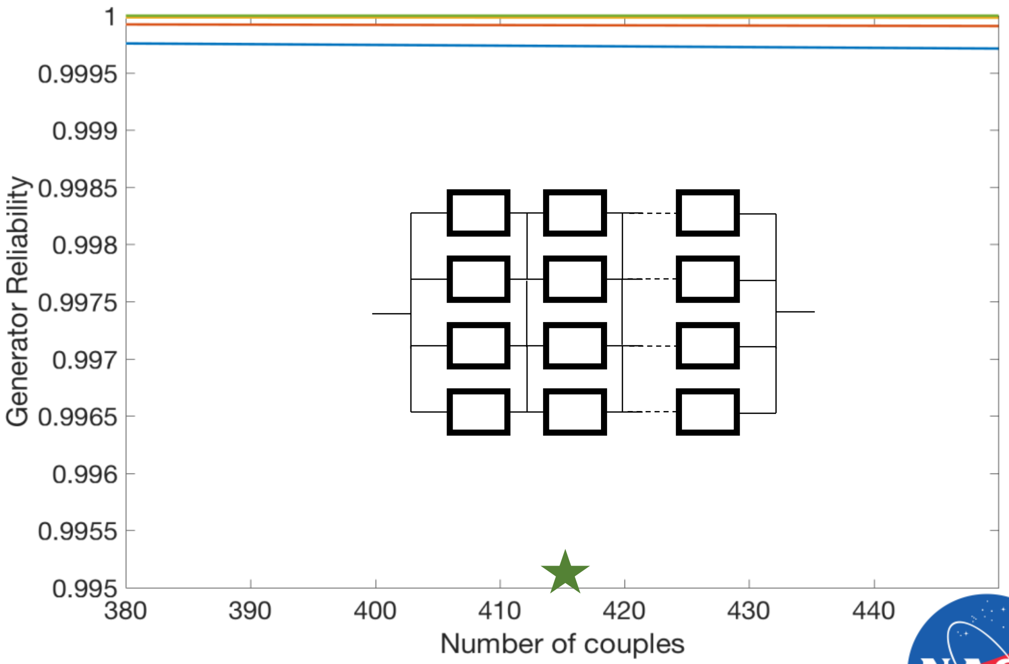
- Each variant is based on the smallest 2 GPHS network, wired in parallel (to maintain consistent voltage)
- 2 GPHS variant has a total of 416 couples (constrained by size)
  - 2 groups of 208 results in 34 V output
  - 4 groups of 104 results in 17 V output
- Voltage can be traded with reliability, or the smallest network can be increased to 4 GPHS size



Proposed variants (artist's concept)



2 strings of 208 to
4 strings of 104



★ Next-gen RTG design point @ 34V
(208 groups of 2 = 416 couples)

★ Alternate design point @17V
(104 groups of 4 = 416 couples)

Conclusions

- Distributing couples in a network to a greater number of strings improves reliability
  - Trade between voltage and reliability
  - Relaxes the couple reliability requirement dramatically
- For a series-parallel network, adding couples above minimum requirement to the strings initially increases the reliability to a peak, then gradually lowers the reliability with additional couples
  - Redundancy does not necessarily result in greater reliability (reliability trades with power margin)
- Greater couple reliability results in less penalty in network reliability for each additional couple
- High generator reliability requires either:
  - Very high couple reliability
  - Strategic electrical network configuration

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract to the National Aeronautics and Space Administration.

Backup

Developing a model: Relevant equations

1. Probability that at least the **minimum number of couples** is operating *(cumulative distribution function)*
   - *m = # of couples in the network*
   - *i = # of couple failures*
   - *j = maximum # of couple failures to meet power requirement*

$$R_P = \sum_{i=0}^{j} \binom{m}{i} R_C^{m-i} [1 - R_C]^i$$

2. Probability of maintaining **electrical continuity:**

$$R_E = \{1 - [1 - R_C]^L\}^W$$

- **Couple** reliability (survival function):

$$R_C = e^{-\lambda t}$$

- **Failure** rate:

$$\lambda = {}^{1}/_{MTBF}$$

- Combining the two requirements for success necessitates an exploration of the **common points** in the sample space